Partitioning Evapotranspiration in Semiarid Grassland and Shrubland Ecosystems Using Diurnal Surface Temperature Variation

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ABSTRACT

The encroachment of woody plants in grasslands across the Western U.S. will affect soil water availability by altering the contributions of evaporation (E) and transpiration (T) to total evapotranspiration (ET). To study this phenomenon, a network of flux stations is in place to measure ET in grass- and shrub-dominated ecosystems throughout the Western U.S. A method is described and tested here to partition the daily measurements of ET into E and T based on diurnal surface temperature variations of the soil and standard energy balance theory. The difference between the mid-afternoon and pre-dawn soil surface temperature, termed Apparent Thermal Inertia (I_A), was used to identify days when E was negligible, and thus, ET=T. For other days, a three-step procedure based on energy balance equations was used to estimate the contributions of daily E and T to total daily ET. The method was tested at Walnut Gulch Experimental Watershed in southeast Arizona based on Bowen ratio estimates of ET and continuous measurements of surface temperature with an infrared thermometer (IRT) from 2004-2005, and a second dataset of Bowen ratio, IRT and stem-flow gage measurements in 2003. Results showed that reasonable estimates of daily T were obtained for a multi-year period with ease of operation and minimal cost. With known season-long daily T, E and ET, it is possible to determine the soil water availability associated with grass- and shrub-dominated sites and better understand the hydrologic impact of regional woody plant encroachment.

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POPULAR SUMMARY

In the semiarid and arid regions of the western United States, woody plants in the form of shrubs have begun to encroach upon traditional grasslands. It is known that shrub-dominated vegetation has a different water demand than herbaceous vegetation, which affects the balance between soil evaporation (E) and plant transpiration (T). This is turn impacts soil water availability, which is the driving force behind this region's biologic, hydrologic, and socioeconomic processes. However, accurate partitioning of water loss between E and T is one of the most important ecohydrological challenges in understanding vegetation dynamics in dryland environments. With better seasonal information about E and T, it should be possible to better interpret the biological and hydrological impacts of woody shrub encroachment and plan for the subsequent socioeconomic consequences related to this land use change.

This paper describes a method to partition the daily measurements of evapotranspiration or ET (total evaporation plus transpiration) which are available from a network of flux stations throughout the western U.S. into E and T based on diurnal surface temperature variations of the soil and standard energy balance theory. Results showed that reasonable estimates of daily T were obtained for a multi-year period with ease of operation and minimal cost. With known values for season-long daily T, E, and ET such as obtained through this study, it is possible to determine the soil water availability associated with grass- and shrub-dominated sites and better understand the hydrologic impact of regional woody plant encroachment.

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SIGNIFICANT FINDINGS STATEMENT

Background: In the semiarid and arid regions of the western United States, woody plants in the form of shrubs have begun to encroach upon traditional grasslands. It is known that shrub-dominated vegetation has a different water demand than herbaceous vegetation, which affects the balance between soil evaporation (E) and plant transpiration (T). This is turn impacts soil water availability, which is the driving force behind this region's biologic, hydrologic, and socioeconomic processes. However, accurate partitioning of water loss between E and T is one of the most important ecohydrological challenges in understanding vegetation dynamics in dryland environments. With better seasonal information about E and T, it should be possible to better interpret the biological and hydrological impacts of woody shrub encroachment and plan for the subsequent socioeconomic consequences related to this land use change.

Approach: To address this issue, a method was developed to partition the daily measurements of evapotranspiration or ET (total evaporation plus transpiration) which are available from a network of flux stations throughout the western U.S. into E and T based on diurnal surface temperature variations of the soil and standard energy balance theory. The approach involved the addition of infrared thermometers to standard flux stations, and using a thermal inertia (I_A) calculation (difference between midday and predawn surface temperatures) to identify days when evaporation from the soil was negligible. Results showed that reasonable estimates of daily T were obtained for a multi-year period with ease of operation and minimal cost.

Significance: The main contribution of this work was a new method to partition on-site measurements of daily total evapotranspiration (ET_D) into daily E and T based on the low-cost addition of an infrared thermometer to existing eddy covariance and Bowen ratio stations. Reasonable estimates of T_D were obtained for clear-sky days when E_D was found to be zero based on the magnitude of the apparent thermal inertia (I_A). The approach is based on instrumentation that can be maintained in place continuously for years with no more expertise and effort than is already required for deployment of energy flux stations.

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The encroachment of woody plants in grasslands across the Western U.S. will affect soil water availability by altering the contributions of evaporation (E) and transpiration (T) to total evapotranspiration (ET). To study this phenomenon, a network of flux stations is in place to measure ET in grass- and shrub-dominated ecosystems throughout the Western U.S. A method is described and tested here to partition the daily measurements of ET into E and T based on diurnal surface temperature variations of the soil and standard energy balance theory. The difference between the mid-afternoon and pre-dawn soil surface temperature, termed Apparent Thermal Inertia (I_A), was used to identify days when E was negligible, and thus, ET=T. For other days, a three-step procedure based on energy balance equations was used to estimate the contributions of daily E and T to total daily ET. The method was tested at Walnut Gulch Experimental Watershed in southeast Arizona based on Bowen ratio estimates of ET and continuous measurements of surface temperature with an infrared thermometer (IRT) from 2004-2005, and a second dataset of Bowen ratio, IRT and stem-flow gage measurements in 2003. Results showed that reasonable estimates of daily T were obtained for a multi-year period with ease of operation and minimal cost. With known season-long daily T, E and ET, it is possible to determine the soil water availability associated with grass- and shrub-dominated sites and better understand the hydrologic impact of regional woody plant encroachment.

INTRODUCTION

Encroachment of woody plants in grasslands has become a common phenomenon across the Western U.S. over the past 150 years (Schlesinger et al., 1990; Van Auken, 2000). This is of particular ecologic interest because these grassland communities have not been invaded by nonnative species, but rather indigenous species have increased because of changes in local abiotic or biotic conditions. Furthermore, there is serious concern that this trend will continue and the change in vegetation composition and structure may be irreversible (Peters et al., 2004).

The impact of this transition on ecosystem function is still unclear, resulting in a multitude of studies contrasting the biological processes in grass- and shrub-dominated sites. These studies have addressed biodiversity (Murphy and Weiss, 1992), vegetation distribution (Guswa et al. 2002; Smith et al. 1995), plant productivity (Lauenroth and Sala, 1992), and plant water use efficiency (Emmerich and Verdugo, this issue (a)). The physical sciences have received similar consideration with studies comparing grassland and shrubland runoff and erosion patterns (Abrahams et al., 1995; Bhark and Small, 2003; Wilcox et al., 2003), streamflow (Wilcox, 2002), soil fertility (Schlesinger et al., 1990; Kieft et al., 1998), energy balance (Small and Kurc, 2003), and soil moisture and texture (Scott et al., 2000; Fernandez-Illescas et al., 2001; Yao et al., in press). Results have shown that the grass-to-shrub transition could have far-reaching impacts on all aspects of ecosystem function ranging from soil microfauna (Schlesinger et al., 1990) to regional rainfall patterns (Taylor, 2000). This, in turn, could have socioeconomic impacts related to land use change as well as climate change (Houghton et al., 1999).

In semiarid and arid regions, these studies have focused on soil water availability, which is the driving force behind ecosystem biologic, hydrologic and socioeconomic processes. Shrub-dominated vegetation has a different water demand from that of herbaceous vegetation, manifesting in the water loss from evapotranspiration (ET). There is evidence that woody plant encroachment may not impact the total ET (Kurc and Small, 2004; Dugas et al., 1996; Phillips, 1992), but it can alter the relative contributions of soil evaporation (E) and plant transpiration (T) to ET. In turn, these shifts in E versus T related to vegetation change can impact net ecosystem production and carbon cycling. This has important implications for resource management strategies and other surface manipulations in dryland ecosystems associated with intensification of land use and climate change (Loik et al., 2004). In a landmark analysis of vegetation dynamics in drylands, Huxman et al. (2005) identified the partitioning of E and T as one of the most important ecohydrological challenges in understanding vegetation dynamics in drylands. That is, with seasonal information about E and T under current conditions, it may be possible to better interpret the biological and hydrological impacts of shrub encroachment and plan for the socioeconomic consequences.

Reynolds et al. (2000) summarized the results of multiple studies in aridlands and reported the very different measurements of the percentage of total ET attributed to T, varying from as little as 7% to as much as 80% in arid and semiarid ecosystems in the American Southwest (Arizona, Nevada and New Mexico). Nonetheless, these studies made the first attempts to interpret the T/ET ratio in terms of vegetation spatial patterns and energy balance (Tuzet et al., 1997), precipitation (Taylor, 2000; Loik et al., 2004), carbon dioxide exchange (Scott et al., in press), geomorphology (Smith et al., 1995) and plant community (Schlesinger et al., 1987).

These studies were carried out over relatively short time periods and did not represent the variability of ET associated with seasonal variability in rainfall. Lane et al. (1983) and Reynolds et al. (2000) used model simulations to better understand the T/ET ratio of desert sites over longer time periods (nine- and 100-year periods, respectively), and still reported values of T/ET varying from 1-58% for grassland and 6-60% (or 15-37%) for shrub-dominated sites. However, with these longer data sets, they could interpret the effects of seasonal precipitation on plant transpiration and net production. Reynolds et al. (2000), in particular, emphasized the link between T/ET and rainfall patterns that explained the great year-to-year variability in results for grass- and shrub-dominated sites. Furthermore, they were able to simulate environmental conditions before and after a "treatment" and to predict the hydrologic consequences of various land uses and management practices. Such simulation models and others (e.g. Laio et al., 2001) offer a handy tool for partitioning ET and evaluating trends and relative variations, however the accuracy of absolute results is uncertain. Guswa et al. (2002) reported that ET estimated with a simple bucket-filling model and a more complex model at one location differed by 50% and the T/ET ratio varied from 55% to 67% over a season.

The goal of this work is to offer a new way to measure, rather than simulate, the T/ET over long time periods with ease of operation and minimal cost. An approach is proposed in which daily ET, measured with a conventional eddy covariance or Bowen ratio technique, is partitioned into E and T using coincident measurements of diurnal soil surface temperature and basic energy balance theory. Instrumentation for these measurements can be maintained in place continuously for years, as demonstrated in this and other studies. Then, with known season-long daily T, E and ET, it is possible to determine the soil water availability associated with grass- and shrub-dominated sites and better understand the hydrologic impact of regional woody plant encroachment.

APPROACH

This approach is based on the assumption that conventional eddy covariance or Bowen ratio instrumentation is in place at a site, with coincident measurements of soil surface temperature, making measurements throughout the day at the commonly used 20- or 30-minute time interval. In this approach, the difference between the mid-afternoon and pre-dawn soil surface temperature, termed Apparent Thermal Inertia (I_A), was used to identify days when E was negligible. It is demonstrated herein that when I_A reached a seasonal maximum, E approached zero. With this set of measurements at a given site, daily ET (ET_D) can be measured; dates for which daily E approaches zero ($E_D \approx 0$) can be identified; and daily T (T_D) can be equal to ET_D, where $T_D = ET_D$.

It is shown here that this approach can provide reliable estimates of T_D for cloudfree days when $E_D \approx 0$. For days not meeting these two criteria, a three-step procedure based on energy balance equations was used to estimate the contributions of E_D and T_D to total ET_D. First, for clear-sky dates when $ET_D \approx 0$, a value of aerodynamic resistance was computed based on the assumption that all available energy was converted to sensible heat (see details below). Second, the thus-calibrated energy balance equations were used to compute an E Index (EI) defined as the ratio of E to potential E (E_p) at midday, and actual E was computed as $E = E_p * EI$. Third, T_D was computed for all "other" days (when $E_D \neq 0$ and/or skies were not cloudfree) by $T_D = ET_D - E_D$.

With this set of measurements and equations, it was possible to partition measurements of ET_D into T_D and E_D for all days in the growing season. Background information about thermal inertia and energy balance equations is given in the following subsections.

Apparent Thermal Inertia

By definition, soil thermal inertia (I) represents the ability of soil to conduct and store heat, where

$$I = (k\rho c)^{1/2}\ [\mathrm{J\ m^{-2}\ K^{-1}\ s^{-1/2}}]. \qquad (1)$$

In Eq. (1), k = thermal conductivity [$\mathrm{W\ m^{-1}\ K^{-1}}$] ; ρ = density [$\mathrm{kg\ m^{-3}}$]; and c = heat capacity [$\mathrm{J\ kg^{-1}\ K^{-1}}$] . Like I, apparent thermal inertia (I_A) also represents the resistance of soil to temperature change. However, it is derived instead from the difference between mid-afternoon and pre-dawn surface (or soil) temperatures, where

$$I_A = (t_{s2pm} - t_{s5am})\ [^{\circ}\mathrm{C}]. \qquad (2)$$

The terms t_{s2pm} and t_{s5am} represent soil surface temperatures measured with a down-looking infrared thermometer (IRT) at times 2:00 pm and 5:00 am, respectively.

In early studies, I_A was loosely related to regional soil moisture (Kahle et al., 1987; Pratt and Ellyett, 1979). Though introduced in the early 1980s based on satellite images of surface temperature (Price, 1977), it was not easily interpreted over a heterogeneous terrain (Price, 1985). That is, I_A responds to changes in soil moisture and mineralogy, but it is also highly sensitive to changes in incoming solar radiation, as well as wind speed, air temperature and vapor pressure. In this application, these fundamental limitations in application of I_A are overcome by 1) computing I_A at one site and interpreting the signal over time rather than space, and 2) combining I_A with an on-site measurements of the surface (in this case, ET) to account for atmospheric conditions.

Energy Balance

The 3-step procedure for estimating T_D, when $E_D \neq 0$ and/or skies were not cloudfree, is based on the energy balance equation, i.e.

$$R_n - G = H + \lambda E \qquad (3)$$

where R_n is the net radiant flux density, G is soil heat flux density and H is sensible heat flux density (all in units of $\mathrm{W\ m^{-2}}$). The λE ($\mathrm{W\ m^{-2}}$) is the latent heat flux density that is a product of the heat of vaporization λ ($\mathrm{J\ kg^{-1}}$) and the rate of evaporation E ($\mathrm{kg\ s^{-1}\ m^{-2}}$). Eq. (3) neglects the horizontal advective flow of heat and water vapor and values of G, H and λE are positive when directed away from the surface. For a bare soil surface when E=0, H can be expressed as

$$H = C_v(t_s - t_a)/r_a \qquad (4)$$

where C_v the volumetric heat capacity of air ($\mathrm{J\ EC^{-1}\ m^{-3}}$), t_s is the soil surface temperature (EC), t_a the air temperature (EC), and r_a the aerodynamic resistance ($\mathrm{s\ m^{-1}}$).

Jackson et al. (1981) wrote the energy balance equation in terms of foliage-air temperature,

$$(t_f\text{-}t_a)=[r_a(R_n\text{-}G)/C_v][((1+r_c/r_a)/\{)+((1+r_c/r_a)\}]\text{-}[VPD/\{)+((1+r_c/r_a)\}], \quad (5)$$

where t_f is the plant foliage temperature (EC), r_c the canopy resistance (s m^{-1}) to vapor transport, (the psychrometric constant (kPa EC^{-1}),) the slope of the saturated vapor pressure-temperature relation (kPa EC^{-1}), and VPD the vapor pressure deficit of the air (kPa). For saturated bare soil, where r_c=0 (the case of a free water surface),

$$t_{sMIN}= t_a + [r_a(R_n\text{-}G)/C_v][(/()+()]\text{-}[VPD/()+()], \quad (6)$$

and for dry bare soil, where r_c=4 (analogous to complete stomatal closure),

$$t_{sMAX}= t_a + [r_a(R_n\text{-}G)/C_v]. \quad (7)$$

where t_{sMIN} is minimum soil surface temperature (EC) and t_{sMAX} is maximum soil surface temperature (EC) for the given meteorological conditions at a given time of day.

The on-site measurements necessary to solve Eqs. (6)-(7) are R_n, VPD, t_a and wind speed (Moran et al., 1994). If R_n over bare soil is unavailable, it can be computed from other meteorological measurements (Jackson et al., 1981) and a value of G can be estimated as a function of R_n, if necessary (Clothier et al., 1986). The value of r_a is notoriously difficult to compute and can lead to high uncertainty in t_{sMIN} and t_{sMAX} (Stewart et al., 1994). However, for this application, since ET is being measured on site, it is possible to invert Eq. (7) for dates when ET_D is near zero and empirically estimate r_a for the site. This value of r_a would theoretically be only dependent upon wind speed and would potentially be much more accurate than theoretical computation.

With t_{sMIN} and t_{sMAX} computed from Eqs. (6) and (7) and measured soil surface temperature (t_{sMEAS}), Moran et al. (1994) determined that at midday

$$E/E_p = (t_{sMAX} - t_{sMEAS})/(t_{sMAX} - t_{sMIN}) \quad (8)$$

where E_p is potential evaporation (W m^{-2}). Then, actual E_D can be estimated by multiplying the daily E_p (E_{pD}) by E/E_p assuming $E/E_p = E_D/E_{pD}$, where

$$E_D = (E/E_p)E_{pD} \quad (9)$$

and

$$E_{pD} = (\Delta R_n) + ((C_v VPD)/r_a)/(\Delta+\gamma) \quad (10)$$

(Allen, 1986) with E_{pD} converted to units of mm/day based on the latent heat of vaporization (2.45 10^6 J kg^{-1}) and density of water (1.0 10^{-3} m^3 kg^{-1}). Finally, daily transpiration can be determined by

$$T_D = ET_D - E_D. \quad (11)$$

STUDY SITE, MATERIALS AND METHODS

The Soil Moisture Experiments 2004 (SMEX04) was conducted during the summer of 2004 in Arizona and Mexico to address overlapping science issues of the North American Monsoon Experiment (NAME) and soil moisture remote sensing programs. As part of SMEX04, two sites in the USDA ARS Walnut Gulch Experimental Watershed (WGEW) were instrumented with automated sensors to measure surface and atmospheric conditions. The WGEW is located in southeastern Arizona with a semiarid climate characterized by cool, dry winters and warm, wet summers. Mean annual precipitation is 356 mm and mean annual temperature is 17 EC.

The Kendall site is dominated by herbaceous vegetation, predominately black grama (*Bouteloua eriopoda*), sideoats grama (*Bouteloua curtipendula*), three-awn (*Aristida sp.)* and cane beardgrass (*Bothriochloa barbinodis*). The soil at the site is dominately Stronghold (Coarse-loamy, mixed, thermic Ustollic Calciorthids) with slopes ranging from 4 to 9%. Only 9 km to the west, the Lucky Hills site is a shrub plant community dominated by creosotebush (*Larrea divaricata*), whitethorn Acacia (*Acacia constricta*), mariola (*Parthenium* incanum), and tarbush (*Flourensia Cernua*). The soil at this site is Luckyhills series (Coarse-loamy, mixed, thermic Ustochreptic Calciorthids) with 3 to 8% slopes (King et al., this issue; Skirvin et al., this issue).

At each site, soil surface temperature was measured with an IRT at 5-minute intervals and precipitation was measured at 1-minute intervals. Volumetric soil moisture (θ) was measured at 3 depths (5, 15 and 30 cm) with Vitel capacitance sensors at 5-minute intervals (Paige and Keefer, submitted; Keefer et al., this issue). Soil temperature was measured at 1-, 2-, 5-, 6-, 15- and 30-cm depths with thermocouples at 20-minute intervals. Meteorological data (including incoming solar radiation and soil heat flux) were measured at 5- and/or 20-minute intervals. These sites were also equipped with flux stations to measure evapotranspiration using a Bowen ratio technique at 20-minute intervals (Emmerich, 2003; Emmerich and Verdugo, this issue (b)).

During the growing season in 2003, measurements of ET and T were made at the Lucky Hills shrub-dominated site. ET was monitored every twenty minutes using the Bowen ratio method (Emmerich, 2003), and shrub transpiration was measured every thirty minutes using the constant heat balance sapflow technique (Scott et al., in press). This shorter, but more comprehensive, data set was used to supplement and clarify the analysis of the 2004/2005 study at Kendall and Lucky Hills.

Thus, data sets of ET, T (in the 2003 study), meteorological data, volumetric soil moisture at 5cm, surface temperature (from IRT), and soil temperatures at multiple depths were compiled to study the partitioning of E and T and the computation of plant WUE. These data were analyzed over an eighteen-month period in 2004 and 2005 encompassing the dry/hot season, the North American monsoon and the dry/cool season, with particular attention to drying periods after storm events. Some analysis was conducted for the growing season only, defined as the time when plants were transpiring, which corresponds to a period from about DOY 220 to 280 at WGEW. Rainfall records for that period and the entire year in 2003, 2004 and 2005 are summarized in Table 1.

RESULTS

As discussed in the previous section, I_A is theoretically related to both surface and atmospheric conditions. This sensitivity is illustrated by the response of I_A to a variety of surface and atmospheric conditions associated with a spring storm at Kendall before the summer vegetation growth (Figure 1). A precipitation event on DOY 147 and 148 resulted in a dramatic decrease in I_A associated with an increase in ET_D (due to increased soil moisture) and an associated decrease in available solar energy (due to cloudiness). For the clear-sky days that followed the storm event (DOY 149-152), I_A steadily increased as ET_D decreased, finally reaching a value similar to that before the storm. However, cloudy conditions on the following day (DOY 153) resulted in another dramatic decrease in I_A without any significant change in soil moisture. This demonstrates the difficulty in interpretation of I_A, and introduces the rationale behind the approach used here.

Apparent Thermal Inertia Related to Soil Moisture and Evapotranspiration

Results showed that I_A was not well related to soil moisture for representative summer, winter and spring storms in 2004 and 2005 at WGEW (Figure 2). At Kendall (grassland) and Lucky Hills (shrubland), the I_A decreased immediately with precipitation, but returned to its pre-storm value within days of the storm, depending on atmospheric conditions. In contrast, surface soil moisture (at 5 cm) reached a peak a day or two after the storm, but continued to decrease for weeks thereafter.

For the same winter and spring storms (when transpiration was known to be zero because vegetation was senescent), the I_A related well with ET_D (Figure 1 and Figure 3b). Generally, the I_A was inversely correlated with ET_D and both measures returned to their pre-storm values within the same time period. For the 2004 summer storm (Figure 3a), the I_A post-storm recovery corresponded to a steep decline in ET_D (related to E_D). This was followed by a more gradual decline in ET_D, related to T_D. This trend was confirmed by the I_A and E_D measurements made at Lucky Hills in 2003 (Figure 4). For two small summer storms, variation (decrease and recovery) in I_A corresponded directly to the measured increase and subsequent cessation of E_D.

As one would expect from these results, the relation between soil moisture at 5cm depth and ET_D is weak in both winter and summer (Figure 5). The ET_D is highly influenced by storm events and solar radiation, whereas the soil moisture has a less dramatic post-storm peak and steadily decreases until the next storm event.

Partitioning E and T from ET with Apparent Thermal Inertia

Based on the results in the previous sections, we postulated that the highest I_A values were associated with cloudfree days when E_D was negligible. We also observed that I_A followed a seasonal trend in which higher values were obtained during the summer when solar radiation was at a maximum. To extract the days when $E_D \approx 0$ and $ET_D \approx T_D$, it was first necessary to detrend the annual I_A time series. For ease of computation, this was done in three 6-month sets, as follows.

For 6-month periods in 2004 and 2005, a polynomial was fit to the highest I_A values in the data stream (Figure 6a). Then, an adjustment was made to all the values to remove the seasonal trend relative to the first I_A value in the data stream, resulting in a detrended I_A' (Figure 6b). Finally, a threshold was determined (10% of the highest value I_A' value) to select only the highest values of I_A' (Figure 6b). For dates which I_A'

exceeded that threshold, we presume that E_D was negligible and $ET_D \approx T_D$. Thus, T_D was estimated for selected dates for predominantly grassland (Kendall) and woody vegetation (Lucky Hills) over the time period 2004 and 2005 (Figures 6c and 6d).

This process is premised on the assumption that the measurement of t_S with the IRT at one site represents the conditions across the site, including both sunlit and shaded (under shrub cover) soils. Tuzet et al. (1997) described a "shade effect" that could affect the partitioning of ET due to variability of soil surface water availability. In 1990 at WGEW, electrical resistance sensors (ERS) soil moisture probes were deployed at Lucky Hills under three bare and three shrub-covered surfaces at 5-cm depths (Hymer et al., 2000). The difference between surface soil moisture between bare and shrub-covered surfaces was only 0.2% (0.002 volumetric soil moisture) over the entire 1990 growing season (DOY 229-280).

This process could be applied using near-surface soil temperature measurements, rather than IRT measurements of soil surface temperature. This might be preferable since the instrumentation is less expensive. We found that the amplitude of I_A decreased with depth in the soil (Figure 7). Nonetheless, I_A' computed from soil temperatures at 1cm produced results similar to I_A' based on IRT measurements (compare results in Figure 8 and Figure 6c).

Deriving T_D when $E \neq 0$ and/or Cloudy Sky Conditions

To this point, T_D has been derived from a combination of ET_D measurements and diurnal surface temperature differences. This approach can be applied only when $E_D \approx 0$ and the sky is predominately clear over the daytime period. It was argued in a previous section that T_D could be determined for days when $E_D \neq 0$ and/or the sky conditions were not clear by using energy balance theory, with a site-calibrated aerodynamic resistance (r_a). The r_a for Kendall and Lucky Hills was computed by inverting Eq. (7) to solve for r_a using measurements of R_n, G, t_a and C_v at 2:00 pm on clear sky days in June 2004 and 2005 when ET_D measurements were near zero. The results show that the r_a value at both sites was relatively stable (ranging from 42 to 63 s m^{-1} at Kendall and 41 to 68 s m^{-1} at Lucky Hills) over a range of wind speeds from 1.7 to 6.6 m s^{-1} (Figure 9). Similar results were found by Holifield Collins et al. (this issue) for Kendall using another dataset. The maximum r_a values for all dates were used to solve the energy balance equations (6) and (7) to derive the maximum- and minimum-possible soil surface temperatures (t_{sMIN} and t_{sMAX}) for midday (2:00 pm) at Kendall and Lucky Hills for input to Eq. (8) and determination of T_D (Eq. 11).

An indirect test of the accuracy of the derived r_a values is to compare the H derived by Eq. (7) with the H measured by the Bowen ratio instrumentation. For clear sky days during the growing season (DOY 220-280) at 2:00 pm in 2004 and 2005, the H derived from Eq. (7) based on empirical r_a values and measured temperatures corresponded well with H measured independently by the Bowen ratio sensors with mean absolute differences (MAD) of 32 W m^{-2} and 35 W m^{-2} for Kendall and Lucky Hills, respectively (Figure 10). These MAD are comparable to differences found between values measured by two Bowen ratio systems at the same location (Houser et al., 1998).

With this confidence in the theoretical approach, we computed t_{sMIN} and t_{sMAX} for each day during the growing seasons (DOY 220-280) at Kendall and Lucky Hills in 2004 and 2005 (e.g., Figure 11a). Based on Eqs. (8)-(11), we estimated T_D for days when $E_D \neq 0$ and/or skies were not cloudfree. We added a rule to this process to avoid the computationally possible, but illogical, situation in which E_D would decrease to zero during the few days after a storm and then increase to greater than zero without any further storm activity. The rule was that once E_D=0, it remained zero until the next rainfall event. Combined with the values of T_D computed from I_A' (e.g. Figures 6c and 6d), the result was a season-long estimate of T_D and E_D with reasonable trends at both sites and both years (e.g. Figure 11b).

Validation 2003

Validation of this approach was based on measurements from a study by Scott et al. (in press) designed to measure ecosystem T_D as well as ET_D at Lucky Hills in 2003. The same series of steps illustrated in Figure 6 for Kendall 2004 were followed to estimate T for clear-sky days when E=0 using I_A' at Lucky Hills in 2003. For all other days, T was computed using the energy balance equations (4)-(11) as described in Section x. The correlation between T estimated with I_A' and T measured with a sapflow technique was good (illustrated with asterisks in Figure 12, MAD = 0.29 mm/d). The correlation between T estimated with the semi-empirical energy balance approach was not as successful (illustrated with circles in Figure 12, MAD = 0.64mm/d). The worst result (absolute difference of 2.1 mm/d) was obtained when the day was cloudy for only part of the day (DOY 236 in Figure 12b). Under these conditions, the surface temperatures computed at 5 am and 2 pm (t_{sMIN} and t_{sMAX}) did not necessarily characterize the E_D and the computation of E_{pD} was unreliable.

The ratio of T and ET for the growing season (T_S/ET_S) in 2003 (DOY 220 to 280) based on measurements by Scott et al. (in press) was 0.84 (Figure 13). The T_S/ET_S based on the estimation approach presented here was 0.76, which was within 10% of the measured value. In both cases, T_s was the dominant component of ET_s during the North American monsoon season at WGEW. Preliminary estimates of T_S/ET_S for the growing seasons in 2004 and 2005 show that T_S/ET_S ranged from 0.50 to 0.79 (Figure 14) and the value depended on rainfall and meteorological conditions that characterized the season (Table 1). Based on analysis of 2004 and 2005 results, E_D is close to zero within a few days of the storm event during the growing season.

CONCLUSION

The main contribution of this work was a new method to partition on-site measurements of ET_D into daily E and T based on the low-cost addition of an IRT to existing eddy covariance and Bowen ratio stations. We showed that reasonable estimates of T_D were obtained for clear-sky days when E_D was found to be zero based on the magnitude of the apparent thermal inertia (I_A). This finding is the most valuable and reliable aspect of this approach. The approach is based on instrumentation that can be maintained in place continuously for years with no more expertise and effort than is already required for deployment of energy flux stations.

A theoretical supplement was added to compute T_D on days when the I_A-based approach is not applicable (e.g. cloudy days or when $E_D \neq 0$), resulting in season-long estimates of T_D and E_D. The theoretical energy balance approach should be refined to account for days with variable cloud conditions. Alternatively, it may be possible to use some empirical information gained from days when E_D is known to be zero to derive an empirical relation between T_D and another site measurement (e.g. surface (5 cm) soil moisture) to partition ET_D on those days.

Future work should continue to explore the soil water availability in grass- and shrub-dominated ecosystems like Kendall and Lucky Hills to better understand the potential impact of woody plant encroachment in grasslands across the Western U.S. There is a great deal of evidence that the T_S/ET_S ratio is sensitive not only to woody plant cover, but to the variation in amounts, frequency and timing of rainfall (Reynolds et al., 2000; Guswa et al., 2002; Bhark and Small, 2003; Loik et al., 2004). These preliminary results will be combined with results from similar data collected in 2006 (a relatively wet monsoon season) to further study this link between T_D/ET_D and such variations in rainfall at WGEW.

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Figure and Table Captions:

Table 1. Rainfall summary (mm) for the growing season at WGEW during years 2003-2005 at Kendall and Lucky Hills sites.

Figure 1. Comparison of volumetric soil moisture at 5 cm at 2:00 pm (θ, %), the apparent thermal inertia derived from IRT measurements at 2:00 pm and 5:00 am (I_A, °C, Eq. 2), and daily ET measured with the Bowen ratio method (mm/d, multiplied by 10 for presentation) for a storm event at Kendall in 2005. Circles indicate the cloudfree days and bars represent daily precipitation (mm).

Figure 2. Comparison of I_A (Eq. 2) with volumetric soil moisture (θ) at 5cm at 2:00 pm for summer and winter storms at Kendall, followed by a long series of cloudfree days. Similar results were found (though not shown here) for Lucky Hills and for the spring storm in 2005. Bars represent daily precipitation (mm).

Figure 3. Comparison of I_A (Eq. 2) with daily ET (multiplied by 10 for presentation) for summer and winter at Kendall (the spring storm was presented in Figure 1), followed by a series of cloudfree days. Similar results were found (though not shown here) for Lucky Hills. Bars represent daily precipitation (mm).

Figure 4. Comparison of I_A (Eq. 2) with daily E (multiplied by 10 for presentation) for two storms in 2003 at Kendall, when E_D was determined from the difference between ET_D (using Bowen ratio) and T_D (using sapflow technique). Bars represent daily precipitation (mm).

Figure 5. The weak relation between surface soil moisture (at 5 cm) and daily ET_D (multiplied by 10 for presentation) for a series of storms in the dry/hot season (DOY120-180), the North American monsoon (DOY 200-270), the growing season (DOY 220-280) and the dry/cool season (near DOY 360). Bars represent daily precipitation (mm).

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Figure 10. Comparison of sensible heat flux (H) at 2:00 pm at Kendall and Lucky Hills measured by the Bowen ratio instrumentation on clear-sky days in 2004 and 2005 during the growing season (DOY 220 to 280) and "estimated" H derived from Eq. (4) based on on-site measurements and the empirically derived r_a (from Figure 9). The MAD is the mean absolute difference between measured and estimated values.

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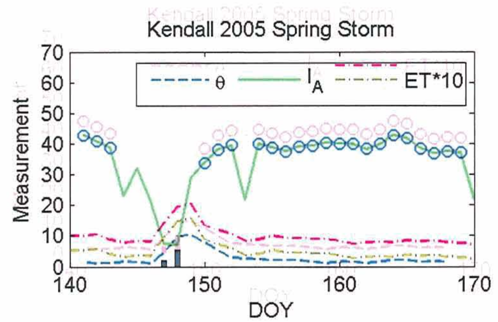
Site and Year	Annual	Growing Season DOY 220-280	
	Total Precipitation	Total precipitation	# of storms
Lucky Hills 2003	245.9	93.2	15
Kendall 2004	294.9	67.7	12
Lucky Hills 2004	219.4	58.4	12
Kendall 2005	162.3	61.0	16
Lucky Hills 2005	223.2	87.2	13



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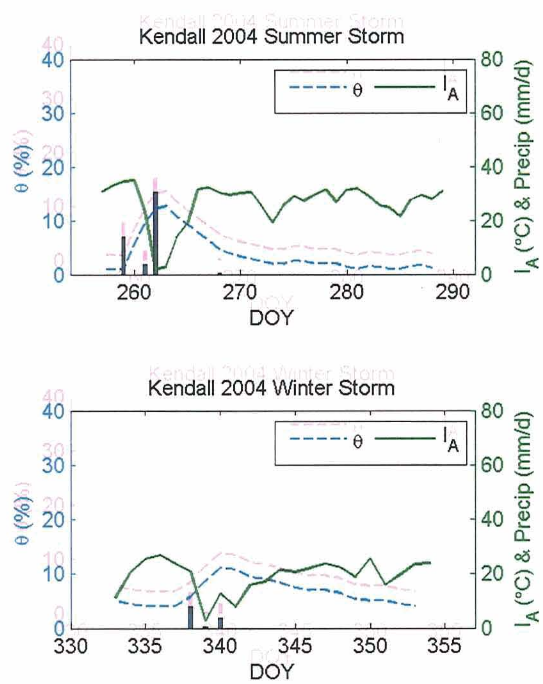

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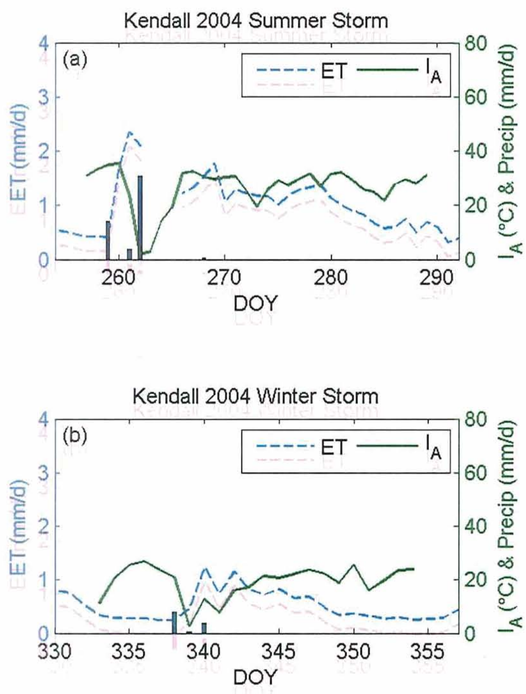

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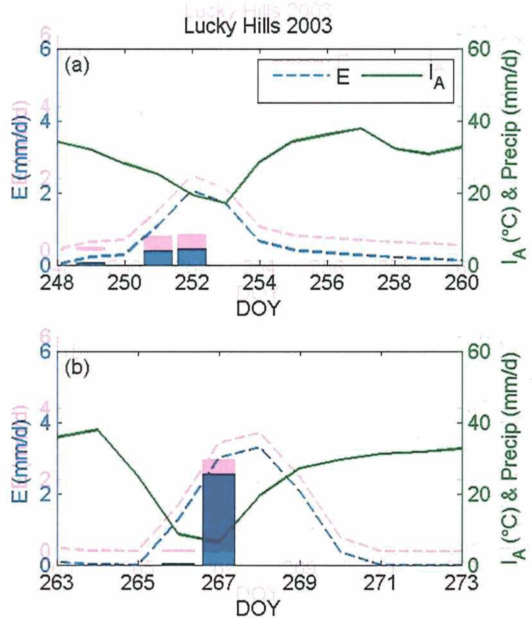

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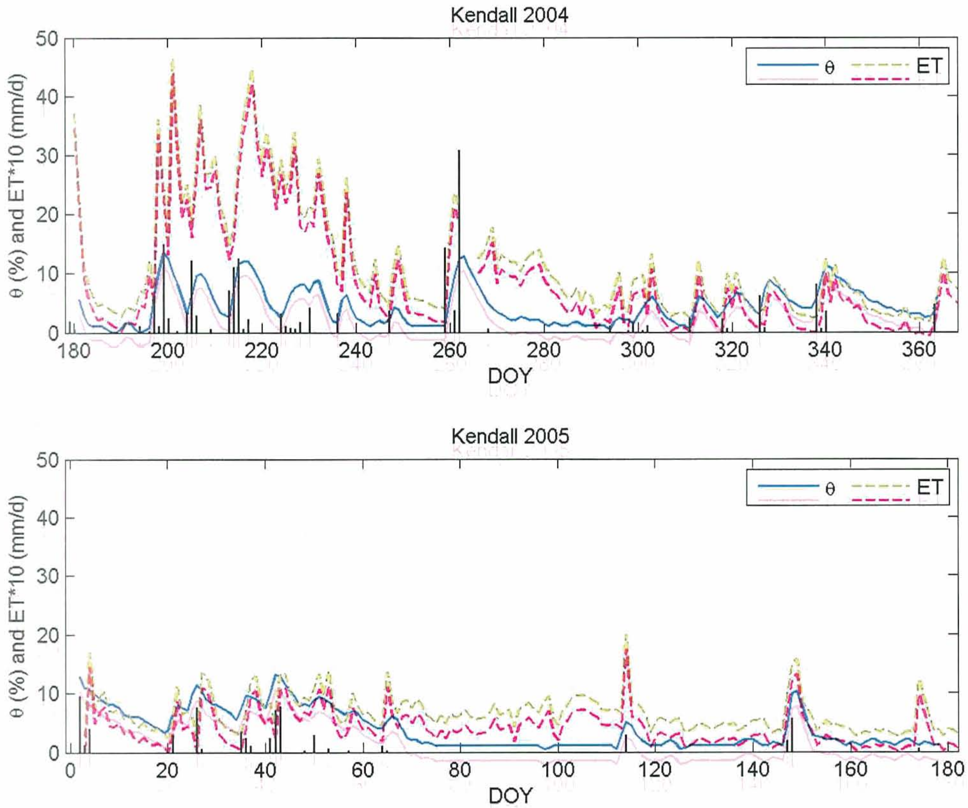

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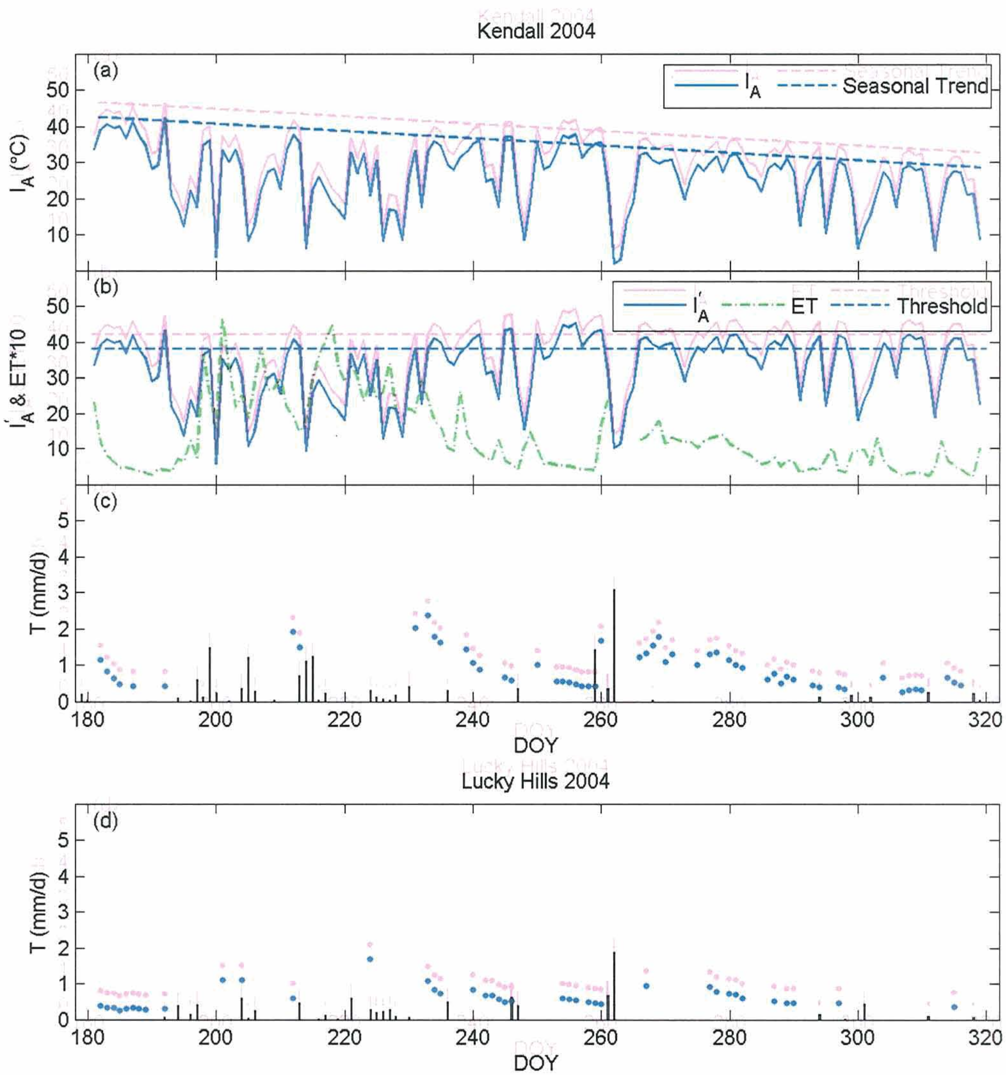

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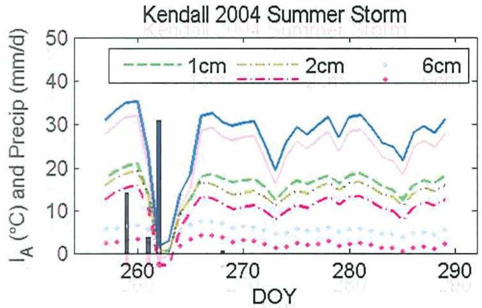

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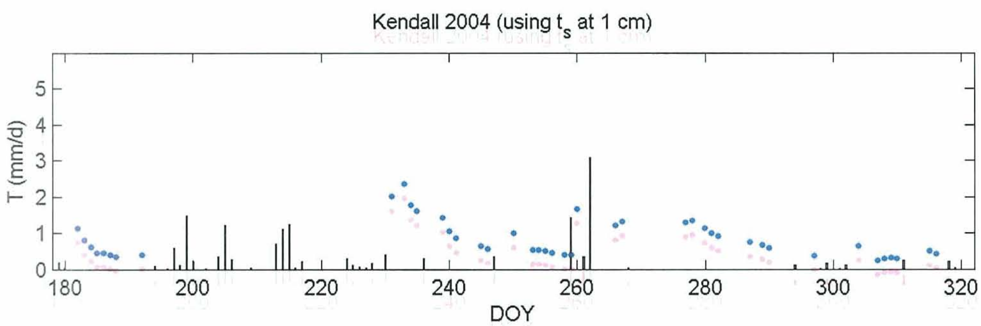

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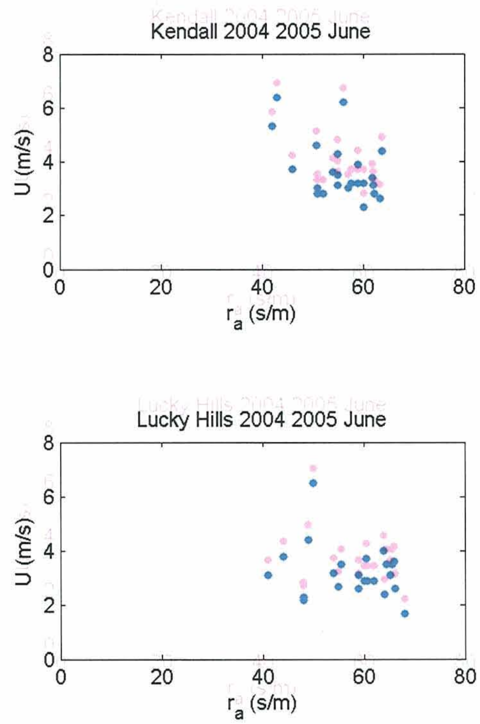

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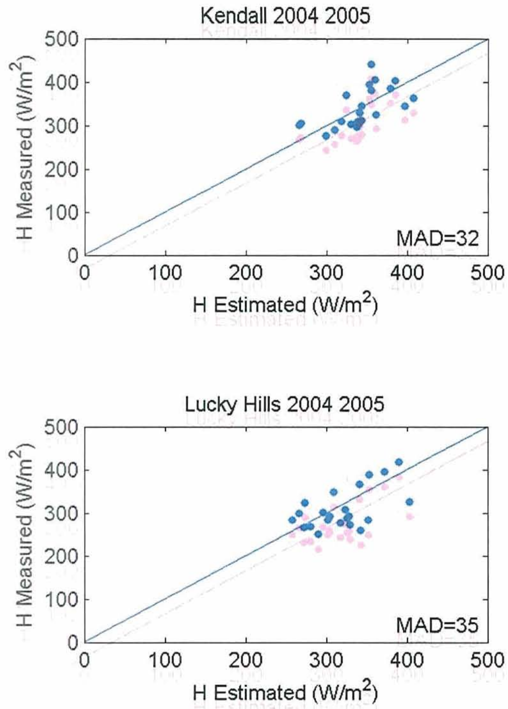

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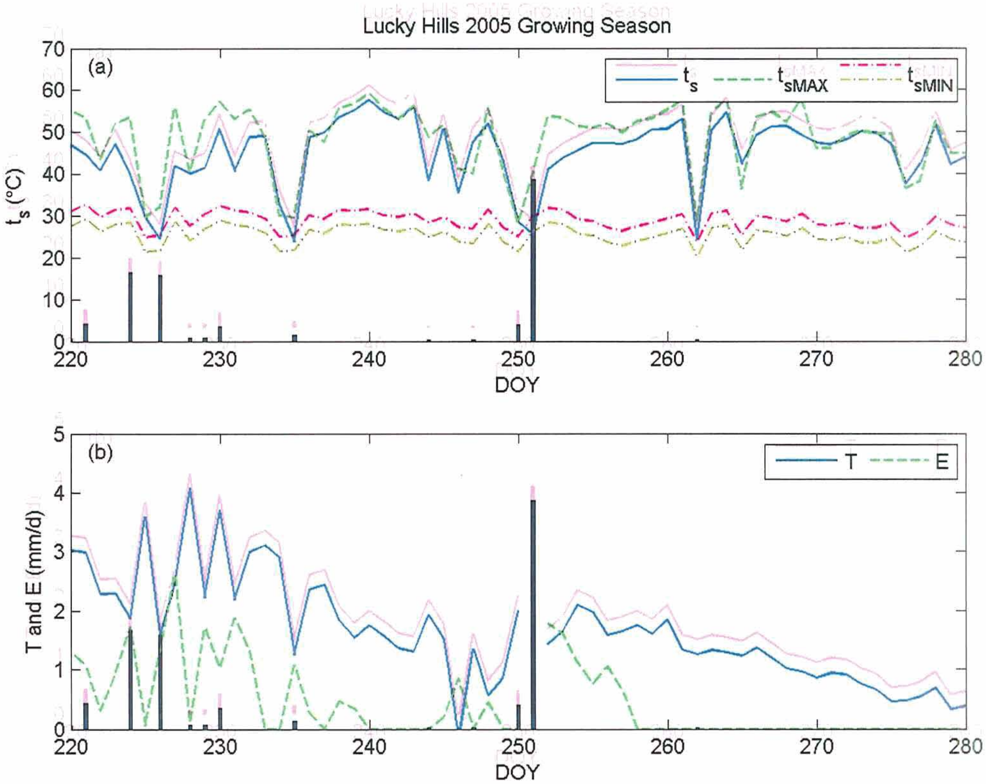

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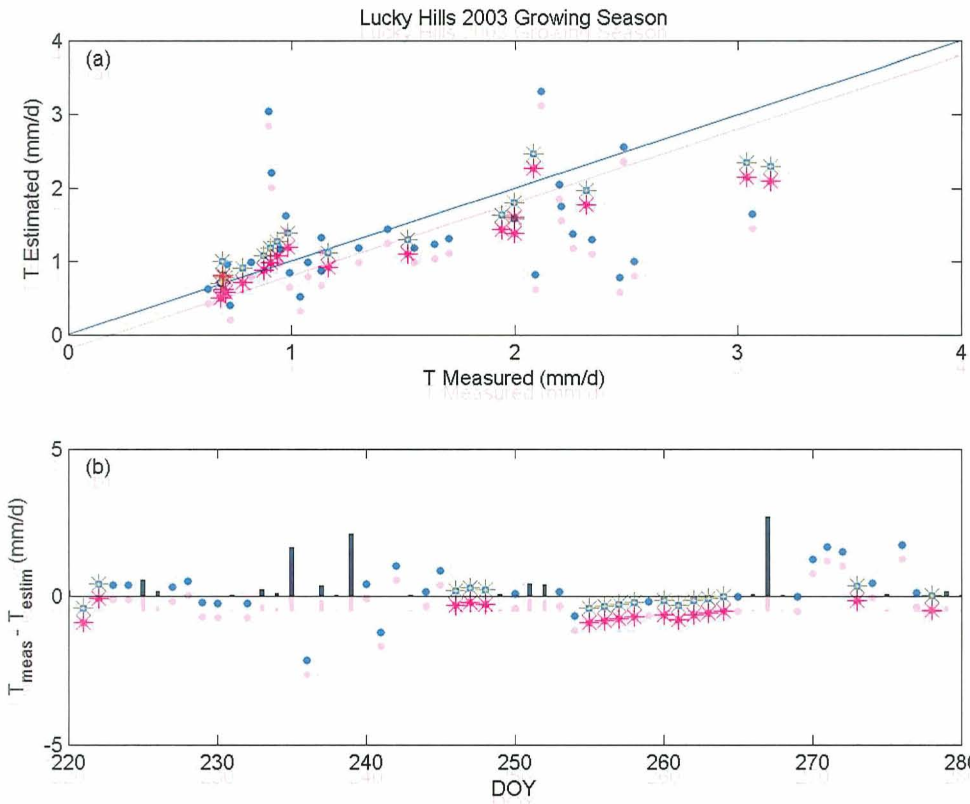

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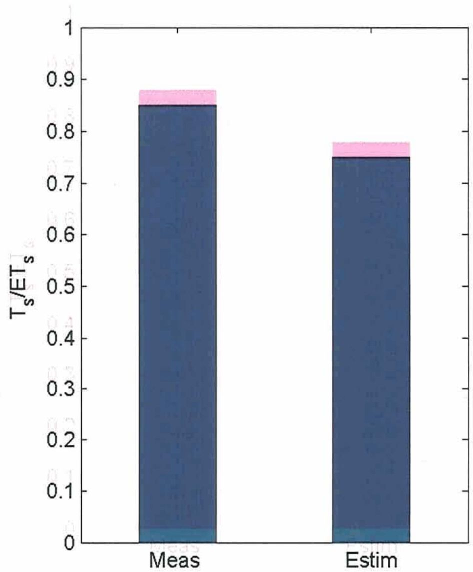

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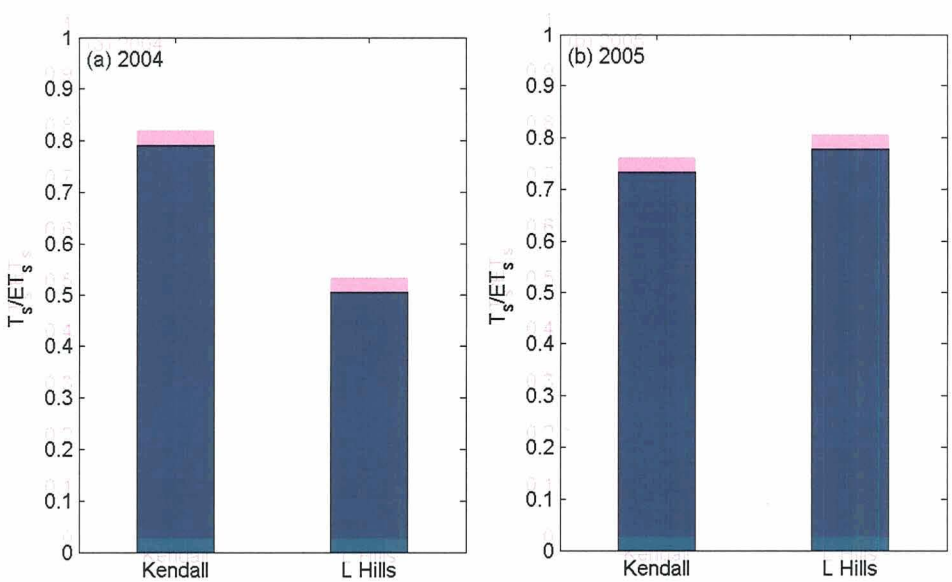

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